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MICROWAVE OSCILLATOR FREQUENCY PULLING VERSUS AN ALL PHASE LOAD

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ABSTRACT

This paper describes microwave oscillator frequency shift or "pulling" with an all phase mismatched load. A derivation of an equation relating frequency shift to oscillator Q, internal round trip isolation, and total external round trip return loss from an all phase mismatch is presented. The derivation is based on the resultant phase error at the oscillator's resonant circuit and is applicable for a variety of microwave oscillators. Two calculator programs using the above equation are also given.

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I. INTRODUCTION

A microwave oscillator gated by an external R.F. switch will shift frequency by the resultant change in magnitude and/or phase of the return loss of the switch states. This effect is commonly called frequency "pulling". Measurement techniques and their application are first presented to familiarize the reader with the problem. Then a derivation of a pulling equation is presented, relating oscillator pulling to frequency, oscillator Q, and internal roundtrip isolation, as well as the total external roundtrip isolation from the all phase mismatch. The derivation is based on the phase error as seen by the tuned circuit, and is shown to be applicable for two-port as well as one port oscillators. Two HP-41CV calculator programs based on the pulling equation end the discussion.

II. FREQUENCY PULLING MEASUREMENTS

Experimentally, it can be shown that the amount of frequency pulling measured is dependent on the phase as well as the magnitude of the reflection coefficient. The reason for this will be shown in Section IV. Because of the difficulties associated with maintaining both a given phase shift and magnitude of return loss and isolation in a complex circuit, it is best to work with worst case values of pulling measurements. This can be accomplished with an all phase load as shown in Figure II-1.

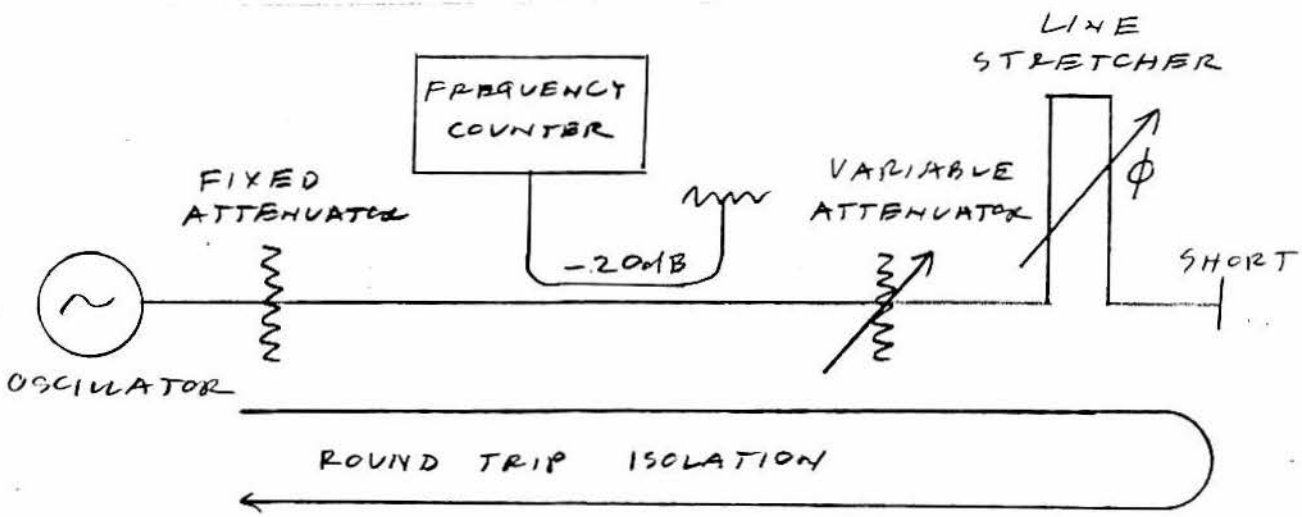


Figure II-1. Pulling Measurement Set-Up

A fixed attenuator is provided at the output of the oscillator to limit the maximum VSWR presented to the oscillator. Pulling will change in many cases with the absolute frequency of the oscillator. In the case of a power oscillator, the attenuator will also serve to prevent damage to the oscillator as a variable step attenuator is changed between settings.

Variable attenuators change return loss magnitude and phase with attenuation. This may shift the frequency of operation enough to affect the pulling. In order to not mask the short circuit return loss, the variable attenuators are placed after the fixed attenuation to minimize the problem.

Placing the line stretcher after the attenuators minimizes line stretcher VSWR and mechanical noise from interfering with the measurements.

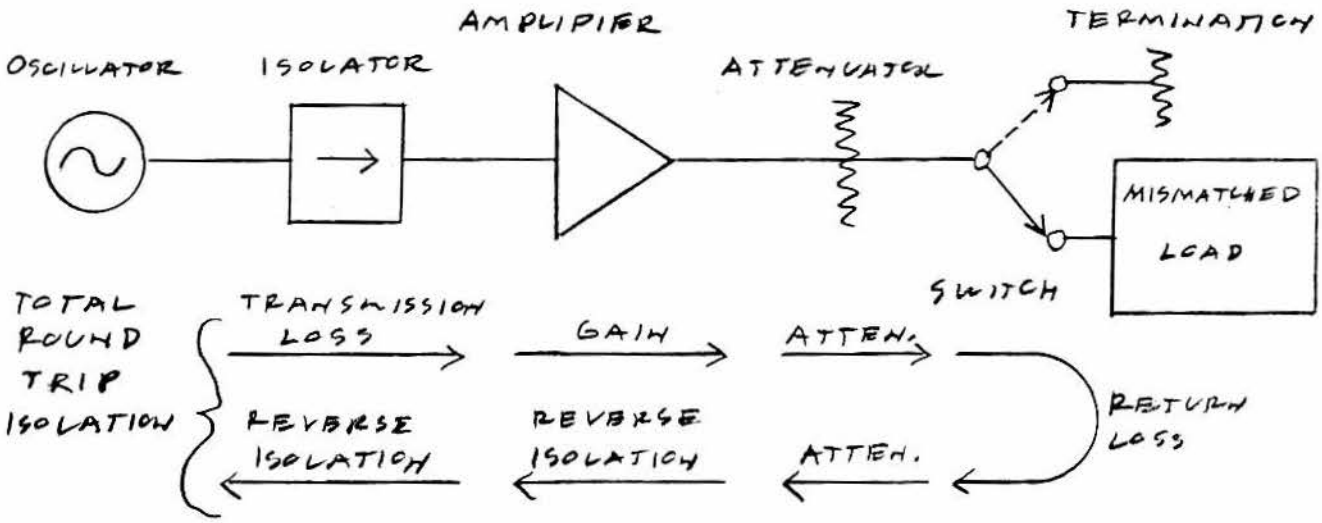
Since passive attenuators are utilized, the total round trip isolation to the variable phase load will be equal to twice the sum of the one-way insertion losses of each component.

The worst case peak to peak frequency excursion is measured at each attenuation setting for an all phase load. In the case of tunable oscillator, this procedure must be repeated for each frequency of interest. The pulling will be found to be approximately proportional to the voltage ratio corresponding to the total round trip isolation of the external circuitry. This will be explained in Section IV.

In some cases, the frequency will appear to jump instantaneously from one value to another with the phase of the load. This has been previously explained by Kurokawa[9] and Hamilton[1]. This can be a serious design problem and should be avoided.

III. Application of Measurements

The results of these measurements can then be applied to the total circuit to predict the worst case behavior of the oscillator with a given round trip isolation to a switched load with a given mismatch. Assume the example circuit shown in Figure III-1.



Example of Oscillator Pulling Situation Figure III-1

The round trip isolation of an isolator is shown to be the sum of its reverse isolation and its forward transmission loss. In the convention used here, both will be considered to be negative numbers.

The round trip isolation of an amplifier is shown to be the sum of its reverse isolation and its gain. Since reverse isolation is a negative number, a loss, and gain is a positive number, the sum of the two may show a degradation in round trip isolation over that of an isolator with the same reverse isolation.

As before, the round trip isolation of the attenuator is twice its one way attenuation. It is interesting to note that an attenuator, if it can be used, will give better total round trip isolation for a given one way isolation than either an isolator or an amplifier.

The round trip isolation provided by a mismatched load is shown to be equal to its return loss, usually a negative number.

In the case of mismatches in both switch states, a vector diagram can be used to determine the relationship of worst case phase error at the resonant circuit of the oscillator of the two switch states. Let the magnitude of the return loss of switch state 1 be greater than that for switch state 2.

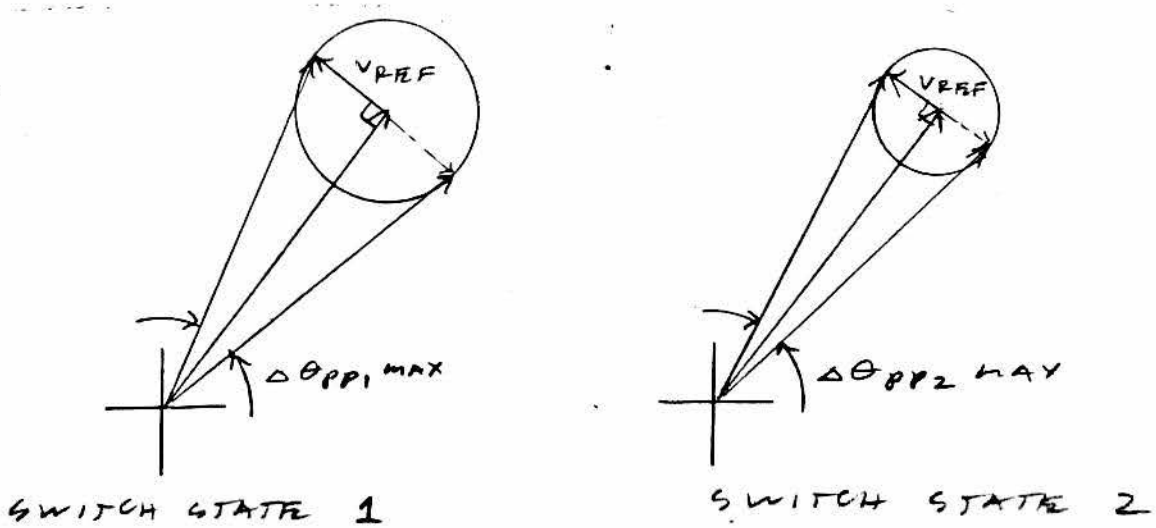


Figure III-2

Note that the phase error ~~(which will be shown later corresponds to pulling)~~ is worse, with all phase loads, for the state with the greatest voltage reflection coefficient. Since the two switch states are on at different times, the errors do not add.

Therefore the switch state with the worst case voltage reflection coefficient will comprise the total worst case round trip isolation, independent of the other state. Therefore for purposes of discussion, it will be assumed that only one mismatched state, the one with the worst case mismatch, will be considered.

The total round trip isolation which is important from the standpoint of pulling is the sum of the individual round trip isolation figures and the return loss of the mismatched load.

Unfortunately, a lot of measurements are required, particularly with a variable frequency oscillator, to predict its behavior with any number of circuit applications. It would be beneficial to be able to predict an oscillators' behavior with only one measurement, at each frequency of operation.

Formulas have been presented in the past to do this, but (eg. compare the pulling equations given by Vemis[4] and Adler[5]) have been found lacking, due to inconsistency, lack of desired derivations, and/or lack of a generalized model of the oscillator, applicable to other situations. A derivation of pulling related to total round trip external isolation including return loss of the mismatched load, internal isolation, and oscillator Q is presented in the following section.

IV. Derivation of Pulling Equation

An equation relating frequency pulling of any single tuned oscillator to circuit conditions can be derived in the following way. First, the phase of the admittance or impedence of an RLC ciruit is related to the frequency of operation.[5,11] A vector diagram is used to determine the phase error at the RLC circuit caused by the reflected voltage. This, in turn, is related to the isolation between the frequency dependent network and the variable all phase load.

Assume that a parallel RLC circuit is used as a model for the frequency determining network:

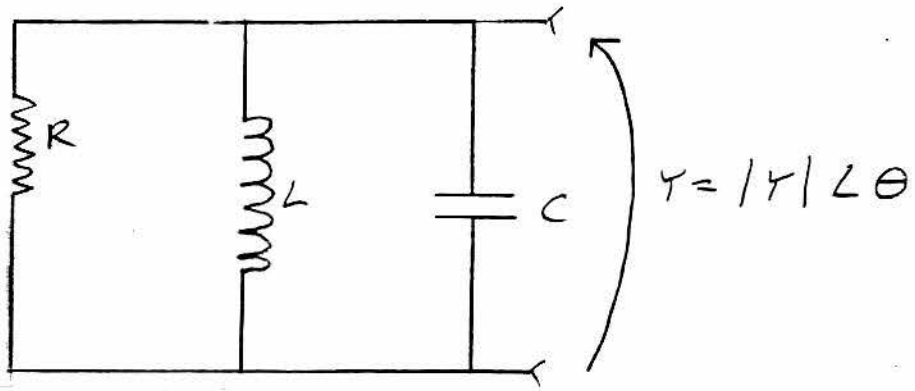


Figure IV-1

$$Y = \frac{1}{R} + J\left(wC - \frac{1}{wL}\right)$$

In terms of $Q = \omega_o RC = \frac{R}{\omega_o L}$,

$$Y = \frac{1}{R} + J\frac{1}{R}\left(\frac{w\ w_o\ RC}{w_o} - \frac{w_o\ R}{w\ w_o\ L}\right)$$

$$Y = \frac{1}{R}\left[1 + JQ\left(\frac{w}{w_o} - \frac{w_o}{w}\right)\right]$$ From Ref. 2, Page 457.

$$\theta = \text{ARCTAN}_{rad}\left[Q\left(\frac{w}{w_o} + \frac{w_o}{w}\right)\right]$$

From Millman and Halkias[11], "...$d\theta/dw$ serves as a measure of the independence of the frequency of all other features of the circuit." "...If initially the phase condition for oscillation

was satisfied at the frequency of oscillation, it will, in general, no longer be satisfied after the alteration of the circuit feature. The frequency must accordingly shift in order once again to restore the loop phase shift to the exact value zero."

Therefore, find the slope:

$$\frac{d\theta}{dw} = \frac{1}{1 + \left[Q\left(\frac{w}{w_o} - \frac{w_o}{w}\right)\right]^2} \cdot \frac{dQ\left(\frac{w}{w_o} - \frac{w_o}{w}\right)}{dw}$$

$$\frac{d\theta}{dw} = \frac{Q\left[\frac{1}{w_o} + \frac{w_o}{w^2}\right]}{1 + Q^2\left(\frac{w}{w_o} - \frac{w_o}{w}\right)^2}$$

Now assume that the pulling is much smaller than the -3 dB bandwidth. Find the slope at $w = w_o$.

$$\frac{d\theta}{dw} = \frac{2Q}{w_o}$$

$$dw = \frac{w_o}{2Q}\, d\theta$$

The pulling can now be related to the change in phase by:

$$\Delta w = \frac{w_o}{2Q} \Delta\theta$$

It is usually more convenient to measure peak to peak pulling.

$$\Delta w_{pp} = \frac{w_o}{Q} \Delta\theta$$

A vector diagram can now be used to relate phase error to an all phase voltage reflection coefficient.

Note that the all phase reflection coefficient used here refers to the reflection coefficient seen at the oscillator frequency determining network from the all phase mismatch and not the static output load impedance.

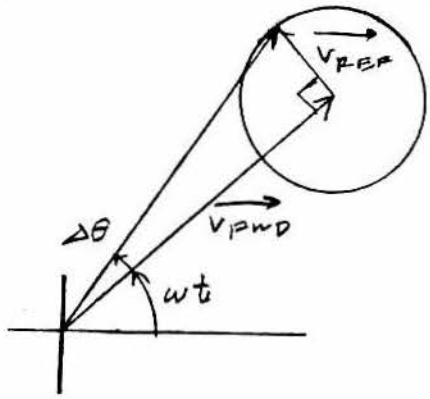


Figure IV-2

$$\Delta\theta = \text{ARCTAN}_{rad} \left| \frac{V_{ref}}{V_{fwd}} \right|$$

$$\Delta w_{pp} = \frac{w_o}{Q} \text{ ARCTAN}_{rad} \left| \frac{V_{ref}}{V_{fwd}} \right|$$

As would be measured with an all phase load.

CAPITAL "I", NOT SMALL "L"

Now let I_I (dB) = the internal round trip isolation of the oscillator between the frequency determining network and the output with an all phase unity reflection coefficient load, due to output matching in the case of a one-port oscillator or due to gain/feedback ratio and output matching in the case of a two-port oscillator.

And let I_X (dB) = the round trip isolation of the external circuitry, including amplifiers, attenuators, etc., including the return loss of the all phase mismatched load.

Note that both I_I (dB) and I_X (dB) will normally be given as negative numbers.

$$I_I(dB) + I_X(dB) = 20\ dB\ LOG10\left[\frac{|\overrightarrow{VREF}|}{|\overrightarrow{VFWD}|}\right]$$

MAKE LIKE ABOVE →

$$\frac{|\overrightarrow{VREF}|}{|\overrightarrow{VFWD}|} = 10^{\frac{I_I(dB) + I_X(dB)}{20\ dB}}$$

$$\Delta w_{pp} = \frac{w_o}{Q}\ ARCTAN_{rad}\left[10^{\frac{I_I(dB) + I_X(dB)}{20\ dB}}\right]$$

Since $w_{pp} = 2\pi f_{pp}$ and $w_o = 2\pi f_o$,

$$\Delta f_{pp} = \frac{f_o}{Q}\ ARCTAN_{rad}\left[10^{\frac{I_I(dB) + I_X(dB)}{20\ dB}}\right]$$

This "pulling" equation now describes the peak to peak change in frequency in terms of fundamental frequency, Q, internal round trip isolation, as well as external round trip isolation to the all phase mismatch. Note that for small angles, the pulling will be approximately proportional to the reflected voltage to forward voltage ratio of the total round trip isolation.

The same result is obtained in the case of a series RLC circuit.

Assume that a series RLC circuit is used as a model for the frequency determining network:

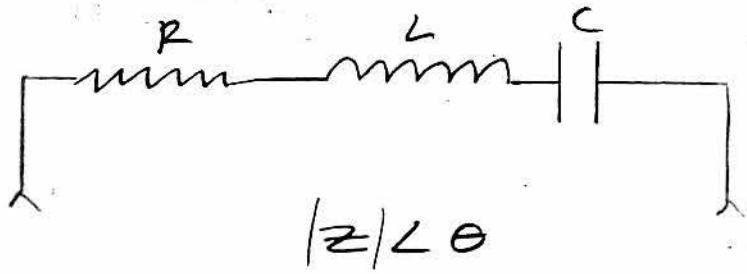


Figure IV - 3

$$Z = R + JwL + \frac{1}{JwC}$$

In terms of $Q = \frac{1}{w_o RC} = \frac{w_o L}{R}$, substitute for "C" and "L";

$$Z = R + \frac{JwQR}{w_o} - J\frac{w_o QR}{w}$$

$$Z = R\left[1 + JQ\left(\frac{w}{w_o} - \frac{w_o}{w}\right)\right]$$

$$\theta = \text{ARCTAN}_{rad}\left[Q\left(\frac{w}{w_o} - \frac{w_o}{w}\right)\right]$$

Note that this is the same phase shift given in the parallel RLC case.

Therefore, by continuing with the derivation as described in the parallel RLC case, the same pulling equation will ensue.

Since the pulling equation holds for both series and parallel frequency determining networks, it whould also hold for a variety of one port and two port oscillators.

A derivation similar to this was previously used to describe injection locking.5

In some cases it is easy to measure Q and internal isolation seperately. Refer to the model of the ideal transformer coupled one port oscillator shown in Figure IV-5.

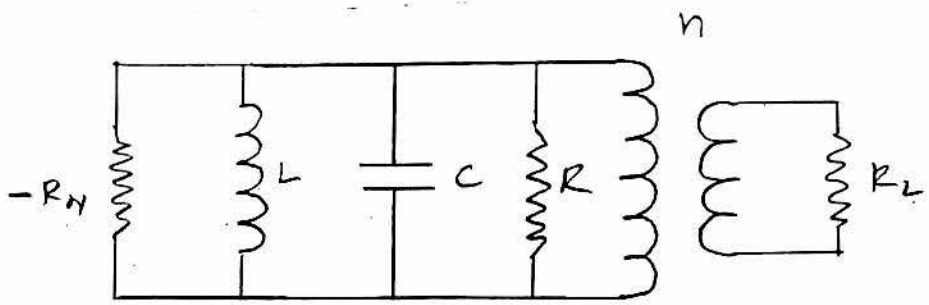
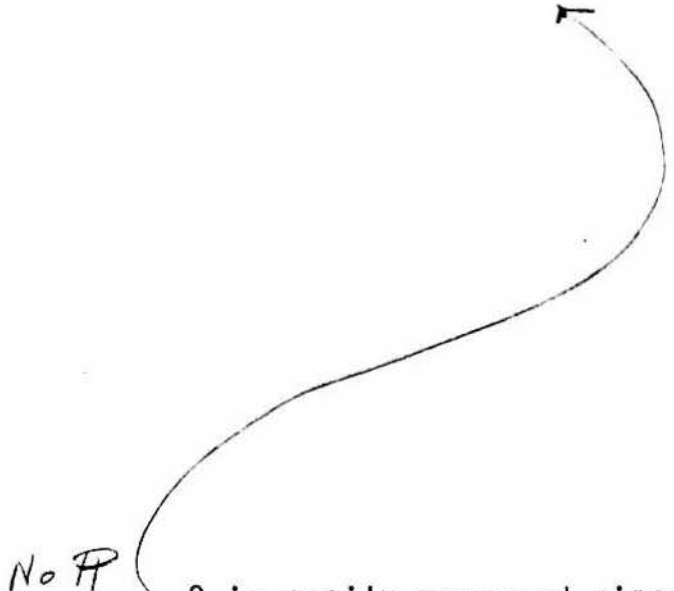


Figure IV-5.

Assume the turns ratio "n" has been selected for maximum power output in the matched condition.

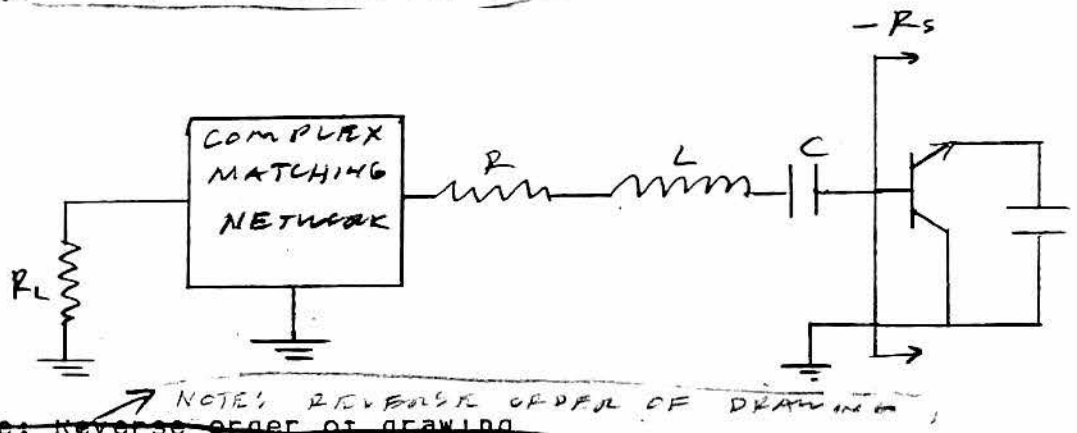


No Γ

Q is easily measured since an ideal transfomer has 0 dB round trip isolation. This is a result of the reflected voltage from the mismatch (not shown in the figure) to the forward voltage ratio being exactly the same on one side of the transformer as on the other side since both the reflected and forward voltages are transformed the same amount, in both magnitude and phase. In this

case, Q is easily measured by frequency pulling7. Remember that V_{REF} as defined here is the refelected voltage returned to the source from the mismatched load ~~at the switch~~. It does not refer to the reflected voltage from any mismatch at the source, which remains constant as the switch position is changed. This is the reason for defining $\frac{|V_{REF}|}{|V_{FWD}|}$ as a total round trip isolation rather than as a reflection coefficient.

In the case of more complex matching networks containing reactances, experimental evidence has indicated that the magnitude of the reflected voltage from the mismatched load may change relative to the forward voltage between the input and output of the network. A Smith Chart or computer must be utilized to calculate the round trip isolation of the network assuming a given all phase reflection coefficient at the load. An example of this is the one port oscillator shown in Figure IV-63.



~~Note: Reverse order of drawing~~

Figure IV-6.

In this case, the internal round trip isolation of the output matching network may take on a significant value. Remember that the matching network will interact with the RLC circuit and will affect the tuning and Q of that circuit. Also the components external to that of the matching network in many cases not equal to 50 ohm terminations will determine its internal round trip isolation. Therefore, 50 ohm S-parameters in general are not suitable.

Noise sideband measurements may also yield useful information on the Q of the tuned circuit independent of the internal matching network.[8] Q influences the sideband noise seen on the carrier. Unfortunately the calculation of Q based on noise sideband power involves a constant which must be determined beforehand for the active device that is utilized in the circuit, be it silicon, gallium arsenide, etc.[3] Whether this would vary from unit to unit within a device family is also unknown. It may be possible to proceed first with the device in a one port ideal transformer coupled oscillator, in which pulling is measured ~~used~~ to determine Q, and the measured sideband noise is used to solve for the constant in the sideband noise versus Q equation. In the case of a two-port oscillator, the situation becomes more complex because of the presence of a nonlinear active device. Refer to the two-port example shown in Figure IV-76.

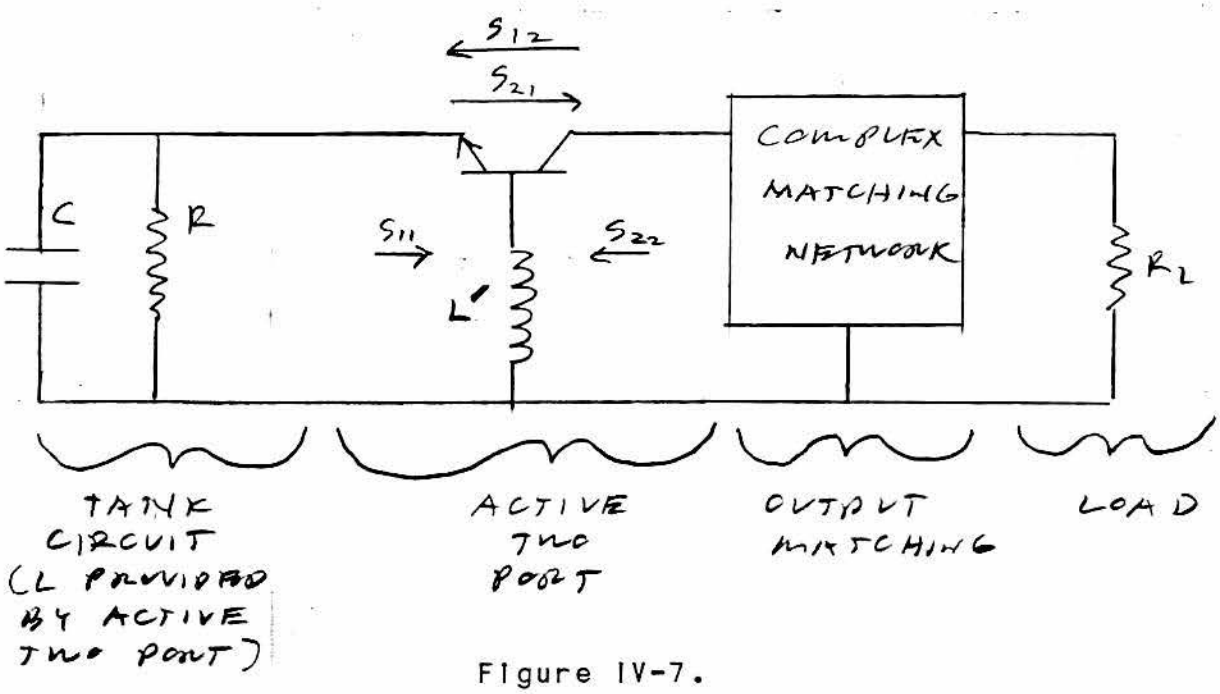


Figure IV-7.

Schemes have been discussed for using small signal S-parameters as a reasonable approximation to obtain useful isolation data. This is occasionally related to the ratio of S21 to S12 of the device with feedback.[6]

In my experience, this does appear to work in certain situations but not in general. A number of reasons probably underlie its failure. First, S-parameters are based on a 50 ohm system, whereas the tuned circuit on port 1 is not 50 ohms. Second, an active device used as an oscillator is not a linear device, even though its output power may be small relative to its bias power. It has to gain limit, thus reducing the effectiveness of the small signal data.

Suggestions for utilizing the computer to transform the all phase load back to the tuned circuit while looking at the oscillator output negative resistance spike on a one port S parameter plot would appear to be more useful.[12,13] The reflected voltage from the output all phase mismatch seen at the frequency determining network is the important criteria.

Computer programs with a mapping routine to transform an all phase load back to the tank circuit are also valuable[6].

Because of the above difficulties in attempting to measure Q and $\Gamma_I(dB)$ separately, it is convenient to simplify the pulling equation and combine the two.

$$\Delta f_{pp} = \frac{fo}{Q} \text{ ARCTAN}_{rad}\left[10^{\frac{\Gamma_I(db) + \Gamma_x(dB)}{20\ dB}} \right]$$

But for small angles; i.e., for $\Gamma_I(dB) + \Gamma_x(dB) \leq -10$ dB, the arctangent function can be dropped. Therefore:

$$\Delta f_{pp} = \frac{fo}{Q}\left[10^{\frac{\Gamma_I(dB) + \Gamma_x(dB)}{20\ dB}} \right]$$

$$= fo\left[\frac{1}{Q}\left(10^{\frac{\Gamma_I(dB)}{20\ dB}}\right)\left(10^{\frac{\Gamma_x(dB)}{20\ dB}}\right)\right]$$

$$\text{LET } 10^{\frac{\Gamma_q(dB)}{20\ dB}} = \frac{1}{Q}\left(10^{\frac{\Gamma_I(dB)}{20\ dB}}\right)$$

In other words, LET $\mathcal{I}q(dB)$ = the combined internal isolation and Q effects on pulling. Therefore:

$$\Delta fpp = fo \left[10 \frac{\mathcal{I}q(dB) + \mathcal{I}x(dB)}{20\ dB} \right]$$

Now the value of $\mathcal{I}q(dB)$ can be obtained by a single measurement of pulling for a given value of $\mathcal{I}x(dB)$. This number, a measure of the "pulling quality" of an oscillator will be applicable at any other value of $\mathcal{I}x(dB)$ for $\Delta fpp << -3dB$ bandwidth. In the case of a voltage controlled variable frequency oscillator, these measurements must be conducted at each frequency of interest, since Q and $\mathcal{I}l(dB)$ will vary.

V. Calculator Programs

Two calculator programs are given which use the pulling equations given in Section 1V.

A. "PULLO"

"PULLO," an HP41CV calculator program, calculates the peak to peak change in frequency for Q, $\mathcal{I}l(dB)$, and $\mathcal{I}x(dB)$, or $\mathcal{I}q(dB)$ and $\mathcal{I}x(dB)$ using the following equations.

(1) $$\Delta fpp = \frac{fo}{Q}\ ARCTAN_{rad} \left[10 \frac{\mathcal{I}l(dB) + \mathcal{I}x(dB)}{20\ dB} \right]$$

(2) $$\Delta f_{pp} \approx f_o \left[10^{\frac{I_Q(dB) + I_x(dB)}{20\ dB}} \right]$$

To use equation (2) press R/S when "Q?" appears as a prompt.

NO SPACE

Program "PULL 0" ~~Version 2~~

00 [ ] GTO [.] [.]

NO SPACE

01 [ ] [LBL] [ALPHA] PULL 0 [ALPHA]

02 [ ] [CLX]

03 [ ] [FIX] 1

04 [XEQ] [ALPHA] RAD [ALPHA]

05 [ALPHA] F? [ALPHA]

Q NOT 0

06 [XEQ] [ALPHA] PROMPT [ALPHA]

07 [STO] 00 ~~CLX~~

08 [ ] [CLX]

09 [ALPHA] Q? [ALPHA]

010 [XEQ] [ALPHA] PROMPT [ALPHA]

11 [ ] [X = 0?]

12 [ ] [GTO] 02

13 [STO] 01

14 [ALPHA] II DB? [ALPHA]

15 [XEQ] [ALPHA] PROMPT [ALPHA]

16 [STO] 02

17 [ ] [GTO] 03

18 [ ] [LBL] 02

19 [ALPHA] IQ DB? [ALPHA]

20 [XEQ] [ALPHA] PROMPT [ALPHA]

21 [STO] 03

22 [ ] [LBL] 01

23 [ALPHA] IX DB? [ALPHA]

24 [XEQ] [ALPHA] PROMPT [ALPHA]

25 [RCL] 03

26 [+]

27 20

28 [÷]

29 [ ] [10x]

30 [RCL] 00

31 [X]

32 [ALPHA] DF PP=
22

33 [ ] [ARCL] [.] X

34 [ ] [AVIEW] [ALPHA]

35 [XEQ] [ALPHA] PSE [ALPHA]

36 [XEQ] [ALPHA] PSE [ALPHA]

37 [ ] [GTO] 01

38 [ ] [LBL] 03

39 [ALPHA] IX DB? [ALPHA]

40 [XEQ] [ALPHA] PROMPT [ALPHA]

41 [RCL] 02

42 [+]

43 20

44 [÷]

45 [ ] [10x]

46 [TAN-1]

47 [RCL] 00

48 [X]

49 [RCL] 01

50 [÷]

51 [ALPHA] DF PP=

52 [ ] [ARCL] [.] X

53 [ ] [AVIEW] [ALPHA]

54 [XEQ] [ALPHA] PSE [ALPHA]

55 [XEQ] [ALPHA] PSE [ALPHA]

56 [ ] [GTO] 03

57 [ ] [GTO] [.] [.]

Registers 00 - f
01 - Q
02 - $\underline{I}$I(dB)
03 - $\underline{I}$q(dB)

B. "SOLVP"

"SOLVP," an HP 41CV calculator program, solves the pulling equation in "PULLO" for $|\underline{I}I(dB)|$ minimum and Q maximum, or $\underline{I}q(dB)$, based on a single measurement of $\triangle f_{pp}$ versus $\underline{I}x(dB)$.

$$\triangle f_{pp} = \frac{fo}{QL} \; ARCTAN_{rad} \left[10 \; \frac{\underline{I}I(dB) + \underline{I}x(dB)}{20 \; dB} \right]$$

To find QMAX, set II(dB) = 0.

$$\text{Therefore: } Q < \frac{fo}{\triangle f_{pp}} \; ARCTAN_{rad} \left[10 \; \frac{\underline{I}x(dB)}{20 \; dB} \right]$$

To find $|\mathcal{I}l(dB)|$ minimum, set Q = 1.

(MOVE UP RELATIVE TO '10')

$$10^{\frac{\mathcal{I}l(dB)}{20\ dB}\uparrow} \quad 10^{\frac{\mathcal{I}x(dB)}{20\ dB}\uparrow} \leq \text{TANrad} \quad \triangle\frac{f_{pp}}{f_o}$$

$$10^{\frac{\mathcal{I}l(dB)}{20\ dB}\uparrow} = 10^{\frac{-\mathcal{I}x(dB)}{20\ dB}\uparrow} \text{TANrad} \quad \triangle\frac{f_{pp}}{f_o}$$

$$\boxed{\mathcal{I}l(dB) > -\mathcal{I}x(dB) + 20\ dB\ \text{LOG}_{10}\left[\text{TAN}\ \triangle\frac{f_{pp}}{f_o}\right]}$$

Note: $\mathcal{I}l(dB)$ and $\mathcal{I}x(dB)$ are normally negative numbers.

$$\triangle f_{pp} \approx \frac{f_o}{Q_L}\ 10^{\frac{\mathcal{I}l(dB)\ +\ \mathcal{I}x(dB)}{20\ dB}} \quad \text{for small angles.}$$

$$\triangle f_{pp} \approx f_o\left[\frac{1}{Q_L}\ 10^{\frac{\mathcal{I}l(dB)}{20\ dB}}\ 10^{\frac{\mathcal{I}x(dB)}{20\ dB}}\right]$$

$$\leftarrow \text{LET}\ 10^{\frac{\mathcal{I}q(dB)}{20\ dB}} = \frac{1}{Q_L}\ 10^{\frac{\mathcal{I}l(dB)}{20\ dB}}$$

(MOVE LEFT)

SPACE ABOVE

$$\Delta f_{pp} \approx f_o \left[10^{\frac{I_q(dB)}{20\ dB}} \quad 10^{\frac{I_x(dB)}{20\ dB}} \right]$$

$$10^{\frac{I_q dB}{20 dB}} \approx \frac{\Delta f_{pp}}{f_o} \quad 10^{\frac{-I_x(dB)}{20 dB}}$$

$$I_q(dB) \approx -I_x(dB) + 20\ dB\ LOG_{10}\left[\frac{\Delta f_{pp}}{f_o}\right]$$

Note: $I_q(dB)$ and $I_x(dB)$ are normally negative numbers.

Program "SOLVP"

00 [ ] [GTO] [.] [.]

01 [ ] [LBL] [APLHA] SOLVP [ALPHA]

02 [ ] [CLX]

03 [ ] [FIX] 1

04 [XEQ] [ALPHA] RAD [ALPHA]

05 [ALPHA] F? [ALPHA]

06 [XEQ] [ALPHA] PROMPT [ALPHA]

07 [STO] 00

08 [ ] [LBL] 01

09 [ALPHA] DF PP? [ALPHA]

10 [XEQ] [ALPHA] PROMPT [ALPHA]

11 [RCL] 00

12 [÷]

13 [STO] 01

14 [ALPHA]]X DB? [ALPHA]

15 [XEQ] [ALPHA] PROMPT [ALPHA]

16 [STO] 02

17 20

18 [÷]

19 [ ] [10x]

20 [ ] [TAN-1]

21 [RCL] 01

22 [1/X]

23 [X]

24 [ALPHA] QL<

25 [ ] [ARCL] [.] X

26 [ ] [AVIEW] [ALPHA]

27 [XEQ] [ALPHA] PSE [ALPHA]

28 [XEQ] [ALPHA] PSE [ALPHA]

29 [RCL] 01

30 [TAN]

31 [LOG]

32 20

33 [X]

34 [RCL] 02

35 [-]

36 [ALPHA] II DB >

28

37 [ ] [ARCL] [.] X

38 [ ] [AVIEW] [ALPHA]

39 [XEQ] [ALPHA] PSE [ALPHA]

40 [XEQ] [ALPHA] PSE [ALPHA]

41 [RCL] 01

42 [LOG]

43 20

44 [X]

45 [RCL] 02

46 [-]

47 [ALPHA] IQ DB =

48 [ ] [ARCL] [.] X

49 [ ] [AVIEW] [ALPHA]

50 [XEQ] [ALPHA] PSE [ALPHA]

51 [XEQ] [ALPHA] PSE [ALPHA]

52 [ ] [GTO] 01

53 [ ] GTO [.] [.]

Bibliography

1. Hamilton, Steve, "Microwave Oscillator Circuits," Microwave Journal, April 1978, pp. 63 - 84.

2. Hayt and Kemmerly, Engineering Circuit Analysis, McGraw Hill, 1962, pp. 451 - 452.

3. Hamilton, Steve, "FM and AM Noise in Microwave Oscillators," Microwave Journal, June 1978, pp. 105 - 109.

4. Vemis, Arthur W., "Specifying Isolation to Limit Frequency Pulling," Microwaves, May 1976, pp. 55 - 57.

5. Adler, Robert, "A Study of Locking Phenomena in Oscillators," Proceedings of the I.R.E. and Waves and Electrons, June 1946, pp. 351 - 357.

6. Strid, Gene, "S-Parameters Simplify Accurate VCO Design," Microwaves, May 1975.

7. Warner, Frank L. and Hobson, Geoff. S., "Loaded Q Factor Measurements on Gunn Oscillators," The Microwave Journal, February 1970, pp. 46 - 53.

8. Kurokawa, Kaneyuki, "Noise in Synchronized Oscillators," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT - 18, No. 4, April 1968, pp. 234 - 240.

9. Kurokawa, K., "Some Basic Characteristics of Broadband Negative Resistance Oscillator Circuits," the Bell System Technical Journal, July - August 1969, pp. 1937 - 1955.

10. Paciorek, L. J., "Injection Locking of Oscillators," Proceedings of the IEEE, November 1965, Vol. 53, No. 11, pp. 1723 - 1727.

11. Millman and Halkias, Electronic Devices and Circuits, McGraw Hill, 1967, pp. 526 - 527, 537 - 538.

12. Basawapatna, Ganesh R. and Stancliff, Roger B., "A Unified Approach to the Design of Wide-Band Microwave Solid-State Oscillators", IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-27, No. 5, May 1979.

13. Conversations with Mike Spencer, Sandia National Laboratories, 1980-1981.